Technique to assess hazards in underground stone mines: the roof-fall-risk index (RFRI)

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Introduction

Mining has been identified as one of four sectors with injury rates that are consistently higher than all other industries within the United State (NIOSH, 2004). Fatal occupational injury rates in 2002 were highest in mining (23.5 per 100,000 workers). Mining was followed by agriculture, forestry and fishing (22.7); construction (12.2); and transportation and public utilities (11.3). Within the underground mining sector, falls of ground comprised about 28 percent of the fatal and 16 percent of the lost-workday injuries from 2000 to 2004 (NIOSH, 2005). The National Institute for Occupational Safety and Health (NIOSH) has a focused research program to enhance the recognition of hazardous conditions and practices and to develop engineering interventions that mitigate conditions most often associated with fall-of-ground injuries.

Many of the hazardous conditions present in the underground mining environment are caused by a combination of geologic and mining-induced factors. Recognizing and assessing the different stability conditions of mine roof strata is a fundamental part of a proactive effort to address falls-of-ground injuries. The implementation of this process allows decision-makers at all levels to determine the potential for a roof fall, a fundamental component of methods to assess risk. This paper proposes a qualitative method to determine a roof-fall-risk index (RFRI) as one possible method to assess the ground-fall hazards associated with underground mining.

Background. Methods aimed at improving the quantitative nature of roof-stability assessment have been developed and used in mining. In the early 1990s, the United Kingdom (UK) developed a code of practice (now Industry Guidance) for rock bolt use as roadway supports that included geotechnical assessment, initial design, design verification and routine monitoring (Arthur et al., 1998). Cartwright and Bowler (1999) provided a UK example of a procedure to assess the risk associated with potential failure or overloading of rock bolt support systems. In the mid-1990s, South African mines developed codes of practice to combat rock fall and rock burst accidents, as required by its 1996 Mine Health and Safety Act (Gudmanz, 1998). Swart and Joughin (1998) discussed the importance of rock engineering in developing this code of practice. Van Wijk et al. (2002) developed a risk-rating system for use in South African coal mines. This risk-rating system aimed to optimize resources and ensure that focus is placed on the areas where it is most required. Lind (2005) demonstrated an integrated risk-management approach that required a basic assessment of physical parameters such as coal seam characteristics, depth below surface and mining conditions. In the United States, Duzgun and

Abstract

The potential for roof falls in underground mines remains a clear and present danger for mine workers. An investigation of ground conditions in nearly 50 percent of the nation's underground stone mines found that the state of roof stability is primarily determined in a limited and subjective manner. These large-opening mines, with roof heights typically 7 m (23 ft) or more, make physical observation difficult. Although some mines use monitoring techniques to gain additional information on roof stability, this practice is usually short term and localized to address ground conditions in a particular section or part of the mine. A roof-fall hazard-assessment technique was developed based on engineering judgment acquired from extensive underground stone mine experience and on examination of the related literature. This technique utilizes observational processes to determine roof fall likelihood. Case-study scenarios offer a realistic picture of model implementation. Providing the mine level decision-maker with an accurate assessment tool to ascertain the level of ground fall hazards is expected to reduce mine worker injuries and fatalities. Moreover, the presences of danger can be overcome with a clear picture of quantified ground conditions.

Einstein (2004) used a statistical analysis of available roof-fall data from mines in the Appalachian Basin to assess the roof-fall risks associated with underground coal mining. In India, Rahaman et al. (2004) discussed the use of microseismic monitoring systems to assess the risk of roof falls. All of these reports either demonstrate or postulate the use of geotechnical parameters to determine the mining system's potential for failure, a fundamental step towards managing the risk associated with fall-of-ground hazards. In many underground U.S. stone mines, especially those with large openings, i.e., >10 and <17 m (>33 and <56 ft) wide with roofs >7 m (>23 ft) high, the state of roof stability is primarily determined in a limited and subjective manner. Therefore, the development of accepted procedures to help determine potential areas of unstable roof will inevitably lead to lower miner exposure to hazardous environments and a measurable reduction in falls-of-ground injuries.

Technique to determine a roof-fall-risk index (RFRI)

The purpose of this paper is to present a qualitative method for determining the RFRI. This method is specifically aimed at underground stone mines where the strata defects that comprise hazardous conditions are difficult to see and where the on-site assessment techniques are typically limited and subjective in nature. The assumptions made in this analysis are that the typical underground stone mine has the following characteristics: wide openings, i.e., >10 and <17 m (>33 and <56 ft); high roofs or back, i.e., >7 m (>23 ft); and relatively flat lying strata. Typical underground stone mines also use blasting techniques to break the rock, scaling to remove loose rocks and, on occasion, some form of rock reinforcement and roof monitoring. The use of this RFRI is relevant only to this experience base and is solely intended to assist in developing a quantitative method to recognize hazardous ground conditions. The target population is the 70 to 90 underground relatively flat lying limestone room-and-pillar mines in the central and eastern portion of the United States. The criteria used to rate strata defects are based on past experience and engineering assessments during examination of more than 50 different underground stone mines. Ten measurable and observable categories are proposed, representing a significant range of defects found at these mines.

An assessment value from "1" to "5" is assigned within each category. Increasing values represent higher potential for failure. The assessment value of "3" is also used when information on a parameter is unknown. The ten defect categories (identified as Nos. 1 through 10 in Table 1) fall into four broad groups: geologic factors, mining induced failures, roof profile and moisture factors.

Geologic factors. The following are the geologic conditions that most often result in increased instabilities in underground stone mines: large angular discontinuities, joint frequency and roof layer thickness and bedding contact strength. Parameters used in assigning an assessment value are identified in Table 1.

Large angular discontinuities: Large angular discontinuities include faults, slips and any other significant geologic structures (Fig. 1, No. 1). They can act to weaken competent roof rock and are often zones where deformations are initiated (mobilized). The influence of angular discontinuities on roof strata stability is well documented (Moebs, 1977; Lagather, 1979). If these parameters are nonexistent, then a value of "1" is assigned. A value of "5" is assigned to roof strata with multiple angular discontinuities and associated weak (low-strength) contacts, implying a high potential for instability from this category. Typically, strong contacts are comprised of sharp surfaces with relatively rough profiles, while weak contacts are comprised of smooth surfaces that are either polished or filled with fine-grained material. If the occurrence of angular discontinuities is unknown, the assessment value is "3."

Joint frequency: Joint frequency has been identified as an important factor influencing roof stability (Krausse et al., 1980). Joints refer to the steeply inclined (nearly vertical) fractures that often naturally occur in rock formations (Fig. 1, No. 2). Joint frequency is comprised of several parameters that help to define the frequency or spacing of joints. Typically, the joints will occur in preferential orientations that can cluster in one or more groupings. It is recommended that the cluster with the lowest average distance between joints be used to evaluate this parameter (Table 1).

Roof layer thickness and bedding contact(s) strength: Roof layer thickness and bedding contact strength have long been recognized as important factors in determining strata stability (Moebs, 1977, Hylbert, 1978, Iannacchione and Prosser, 1998). It is the interaction of these two characteristics that controls the development of separate roof beams and partially controls how they deform (Fig. 1, No. 3). Massive strata, void of distinct geologic layers, tend to have few continuous, horizontal bedding plane structures, making for stable strata conditions. These strata have an assessment value of "1." Almost without exception, mine roofs with wide spans are comprised of relatively strong layers. Layers greater than 1 m (3.3 ft) in thickness are often observed as stable. If these layers are bonded by weak bedding contacts, then the strata are typically less stable. As the roof layers incrementally thin below 1 m (3.3 ft) in thickness, the associated beam deformation or sag can increase, raising the probability of failure. Layers less than 0.25 m (0.82 ft) thick have often been observed as unstable and present a high probability for excessive roof beam sag, especially when they are bounded by weak contacts. In this case, an assessment value of "5" is assigned. The parameters in this category could easily be modified to match local mining experiences.

Mining-induced failures. Mining-induced failures are a direct reflection of strata defects produced as a result of mining. There are four important categories of mining-induced failures in underground stone mines: shear rupture surfaces, joint separation, lateral strata shifting and vertical strata separation.

Shear rupture surfaces: Shear rupture surfaces are typically found in association with buckling of roof layers less than 1 m (3.3 ft) thick. This buckling failure is caused by excessive levels of horizontal stress, producing a low-angle shear rupture surface with a sharp contact and covered with a powder-like rock dust residue (Fig. 1, No. 4). If the occurrence of angular discontinuities is unknown, the assessment value is "3." When the immediate roof layer buckles, the relatively straight shear rupture surface is observable.

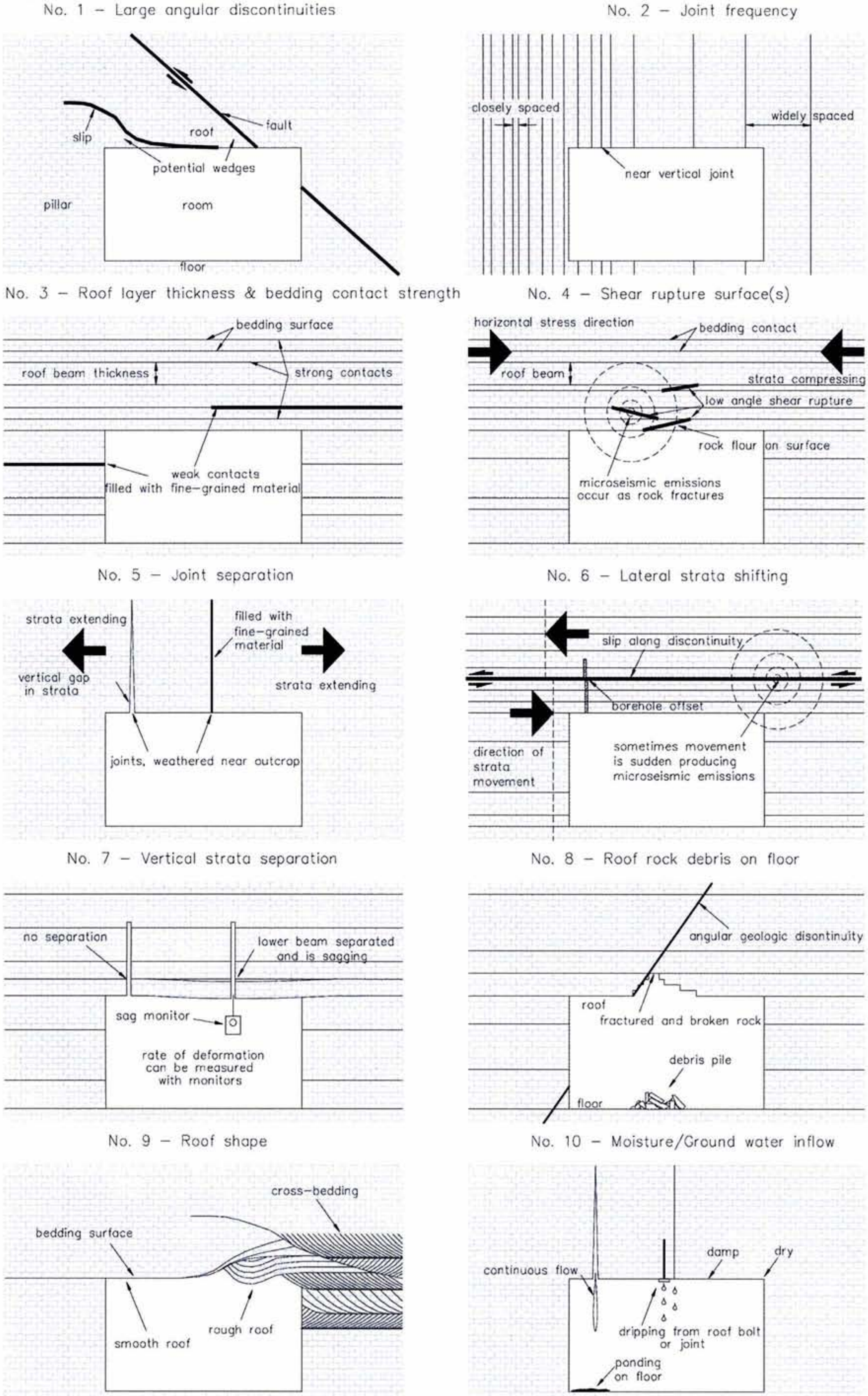
Table 1

Defect categories for determining the RFRI in underground stone mines.

Category	Parameter	Assessment value	Weight	Catagory value
Geologic factors:				
1 Large angular discontinuities	None	1	1	___
	One, strong contact	2		
	One, weak contact	3		
	More than one, strong contact	4		
	More than one, weak contact	5		
	Unknown	3		
2 Joint frequency	None	1	1	___
	Widely spaced, >1 m (>3.3 ft)	2		
	Moderately spaced, 0.25 to 1 m (0.82 to 3.3 ft))	4		
	Closely spaced, <0.25 m (<0.82 ft)	5		
	Unknown	3		
3 Roof layer thickness and bedding contact strength	Massive, >1 m (>3.3 ft) layers)	1	1	___
	Strong bedding contacts in immediate roof, 0 to 3 m (10 ft)	2		
	Weak bedding contact(s) in immediate roof, 0 to 3 m (10 ft))	3		
	Rock layers 0.25 to 1 m (0.82 to 10 ft) with weak bedding contact(s)	4		
	Thin layers, <0.25 m (<0.82 ft). with strong bedding contact(s)	4		
	Thin layers, <0.25 m (<0.82 ft) with weak bedding contact(s)	5		
	Unknown	3		
Mining induced failures:				
4 Shear rupture surfaces	None	1	2	___
	Small shear, cutter <1 m (<3.3 ft)	3		
	Large shear, cutter >1 m (>3.3 ft)	5		
	Unknown	3		
	Microseismic emission at background level	1		
	Microseismic emission elevated and clustered	3		
5 Joint separation	None	1	2	___
	Noticeable or measurable	5		
	Unknown	3		
6 Lateral strata shifting	None	1	2	___
	<20 mm of offset or partial vertical drill hole offset	3		
	>20 mm of offset or complete vertical drill hole offset	5		
	Unknown	3		
7 Strata separation	None	1	2	___
	Slight (barely detectable)	3		
	Significant, >5 mm	5		
	Unknown	3		
Roof profile:				
8 Roof rock debris on floor	None	1	2	___
	Slight (widely spaced)	2		
	Moderate	4		
	Significant (continuous)	5		
	Unknown	3		
9 Roof shape	Smooth	1	1	___
	Intermediate	3		
	Rough	5		
	Unknown	3		
Moisture factors:				
10 Moisture/groundwater	None	1	1	___
	Damp roof	2		
	Drippers	4		
	Steady flow	5		
	Unknown	3		
Sum all category values =				___
Multiplied by 1.11 =				___
Microseismic activity adjustment: no microseismic clustering subtract 5; clustering add 25; 0 if unknown				___
Roof deformation rate adjustment: no roof deflection movement subtract 5; constant deflection add 15; accelerating deflection add 30; 0 if unknown				___
RFRI =				___

FIGURE 1

Sketch of parameters associated with ten defect categories.



Joint separations: Joint separations occur when nearly vertical fractures begin to expand or open up (Fig. 1, No. 5). This can signal a potentially unstable condition, confirming that strata extension is occurring and the strata have lost considerable strength. Because most underground stone mine roofs have some level of vertical jointing and horizontal bedding plane contacts, most roofs are comprised of blocks of varying sizes that are supported by the confining stresses in the immediate roof beam. When strata extension occurs, the roof blocks are no longer confined and are prone to fall to the ground under the forces of gravity. If no joint separation is observed, then the assessment value is "1." Because the parameters used to define separation are limited, any noticeable or measurable separation of a vertical joint is assigned a value of "5."

Lateral strata shifting: Lateral strata shifting is a condition caused when roof layers move in different directions along bedding contacts (Fig. 1, No. 6). While it is difficult to directly link this category with roof falls, it is commonly recognized as a hazardous condition (Zhang and Peng, 2001). In some mines, lateral strata shifting is associated with large-scale movement along a fault plane or a large angular discontinuity. The level of strata offset on either side of the shifting surface can be an indication of the magnitude of movement. If no lateral strata shifting occurs, then the assessment value is "1." If less than 20 mm (0.8 in.) of offset is observed where the surface intercepts the mine roof or rib, then the assessment value is "3." If the offset is >20 mm (0.8 mm), the assessment value is "5." Many of these lateral offsets do not intercept the mine roof or rib and can be hidden from view within the immediate roof. A proven technique to detect these surfaces is to drill vertical boreholes on a regularly spaced pattern. This technique has been used in coal mining to successfully determine the magnitude and direction of strata shifting (Mucho and Mark, 1994).

Vertical strata separation: Vertical strata separation is a condition caused when roof layers separate from one another and sag into the mine entry (Fig. 1, No. 7). The association of roof layer deflection with roof falls is well established and has been a subject of many investigations (Parker, 1973; Maleki and McVey, 1988; Iannacchione and Prosser, 1998). While vertical strata separation can be determined by many methods, a basic requirement is a vertical borehole drilled into the roof and some means to observe and locate separations and determine their magnitude. Often, this is accomplished with devices such as a simple scratch tool, a borescope or a roof deflection monitor. If no separations exist in the immediate roof, then the assessment value is "1." If the separation is barely detectable or open, then the value is "3." If the separation is easily detectable (>5 mm or 0.2 in.), then the value is "5."

Roof profile. The profile of the roof provides a good indication of what damage has occurred to the roof and potentially what damage will occur based on its shape. This damage could be inherent to the rock or it could be induced by blasting or scaling. The two categories that help to define the roof profile are the roof rock debris on the floor and roof shape.

Roof rock debris on the floor: If an entry is being or has been damaged by existing defects or by blasting or scaling, evidence of this damage is typically found deposited on the mine floor (Fig. 1, No. 8). It is vitally important that this information be retained by the mining operation in some manner. If the floor is cleaned after debris has fallen from the roof and no record is made of it, then this valuable piece of information will be lost. One has to make sure that debris from blasting and scaling the roof and ribs is not confused with roof rocks that have fallen without this operational-induced assistance. If no roof rock debris is observed, then the assessment value is "1." Increasing amounts of debris produce higher assessment values. A value of "5" is typically associated with a significant pile of broken rocks that covers a portion of the mine's entry.

Roof shape: It has been established that the shape of the roof can provide some indication of the future performance of the roof (Iannacchione and Prosser, 1998). In general, a smooth roof is desirable in underground stone mining and typically represents a stable state (Fig. 1, No. 9). In this case, the assessment value is "1." Conversely, if the roof is highly irregular with pronounced swales and troughs, the potential for unstable conditions increases and the assessment value is "5." Sometimes this condition is caused by inherent weakness within the roof rocks. Other times the rougher looking roof is a result of roof rocks damaged by blasting or scaling.

Moisture factors. In mining, the physicochemical effects of water can act to reduce the strength of a mine roof (Unrug, 1997). Also, water pressure in fractures may be strong enough to cause roof instabilities. This condition is particularly acute in shallow, large-opening stone mines where extreme humidity conditions, especially in the summer months, reduce roof rock strength. Additionally, the closeness of the mine to the surface places the mines above drainage. This condition promotes the development of weathered joints with variable water flow conditions. Standing or flowing water in prominent fracture systems can exert considerable destabilizing forces within the roof.

Moisture/groundwater inflow: The assessment values for moisture/groundwater inflow characteristics are the following: if the roof is dry and no water is observed, the assessment value is "1"; if the roof is damp, the value is "2"; if dripping occurs, the value is "4"; and if the flow of water from the roof is steady, the value is "5."

Monitoring data and its impact on assessment values

To this point, parameter characteristics of the proposed method to assess roof-fall hazards have been determined with information readily available at any mine site with a means of accessing and drilling the roof. Because underground stone mines are all drill-and-blast operations, every mine in the United States has the basic ability to access and drill the roof. However, if this were the only information that was available to decision makers, then ones ability to more accurately assess stability conditions would be limited. In fact, some mines use advanced monitoring techniques to gain additional valuable information about roof stability. This practice has developed, in part, because of difficulties in accurately observing roof conditions when room heights exceed 7 m (23 ft). Another reason is the need to assess roof-rock behavior above the immediate roof, which is entirely out of the decision-maker's view. As a result, a diverse range of roof-deflection monitoring devices and some geophysical techniques have been or are being used to detect roof-rock defects.

Roof-deflection measurements. Roof-deflection-monitoring techniques have long been employed in underground mining to monitor roof behavior (Parker, 1973b; Kaiser, 1981, Maleki and McVey, 1988; Iannacchione et al., 2004a). Typically, these are mechanical or electro-mechanical devices that allow for the measurement of displacement between two or more known points within a roof borehole or between the mine's roof and floor. Sometimes they are simple tools, such as a scratch tool, that allow the operator to remotely feel or detect the crack or separation within a roof borehole. Roof-deflection measurements are known to produce unambiguous assessments of strata separation characteristics. Monitoring roof beam sag and roof-to-floor convergence provides an opportunity to collect values of roof deflection measurements that can be used to adjust the RFRI values.

Roof-deformation-rate adjustment: Three general conditions are characterized when measuring roof deflection. If measurements indicate that no roof deflection is taking place, the strata can be temporarily considered to be stable. In this first condition, the RFRI is reduced by 5 (Table 1). The second condition is when a measurable level of roof deflection persists for a period. The magnitude of this value is site specific in nature and has been found to range between a few tenths of a millimeter to several millimeters per day. This condition suggests the roof is no longer stable but still may not be on a path that will lead to a failure. There are many examples where roofs with this amount of deflection have temporarily stabilized, in some cases for long periods of time. If this condition occurs, the RFRI is increased by 15. It should be noted that when roof deformations occur, it might be advisable to construct some form of notification and/or barrier to limit entry into the area. The third condition is when the rate of deflection increases on some type of regular basis, such as from one day to the next or perhaps one week or one month to the next. This condition suggests the roof is in an unstable state. If this condition occurs, the RFRI is increased by 30.

Microseismic emissions. Numerous geophysical techniques exist for detecting zones of potential roof instability, including cross-hole seismic tomography, ground-penetrating radar and the monitoring of microseismic emissions. Maleki et al. (1992) detected the development of mine roof fractures up to 15 m (50 ft) into the mine roof. Also, Molinda et al. (1996) used ground-penetrating radar to image a known geologic discontinuity at NIOSH's underground Lake Lynn Laboratory. The use of microseismic emissions information has been discussed to assess risk for South African deep hard rock mine stability (Stewart and Spottiswoode, 1996) and Indian coal mine roof falls (Rahaman et al., 2004). Recently, microseismic emissions have been used to identify zones of roof rock instability at an operating stone mine in Pennsylvania (Iannacchione et al., 2004b).

Microseismic activity adjustment: An adjustment to the RFRI value can be made if adequate microseismic monitoring information exists. Clustering of microseismic events in time, and within a relatively well-defined area of the mine, can signal that rock fracturing is occurring and that the strata may be unstable. Clustering in time is defined by microseismic activity far in excess of the normal background rate. Clustering in space is defined by the microseismic activity occurring within the same general area. The location accuracy of microseismic events can greatly influence spatial clustering. If microseismic activity does not cluster, the strata are most likely not producing new fracture surfaces. In this case, the RFRI is reduced by 5 (Table 1). If microseismic emissions cluster, then the RFRI is increased by 25 (Table 1).

Determining the relative probability of roof falls

Roof-fall-hazard variations can be expressed as a risk index. A mathematical expression can be used to calculate the roof-fall-risk index (RFRI) and is defined as

$$RFRI = \Sigma\,(AV*W) / \Sigma\,(MAV*W) \qquad (1)$$

where

AV is the assessment value for each defect category;
MAV is the maximum of assessment value of each category, or 6; and
W is the weighting of each category.

Because the defect categories affect the performance of underground stone mine entries to different degrees, it is necessary to independently weight each of the ten categories (Table 2). The defect categories more detrimental to entry performance are Categories 4, 5, 6, 7 and 8 were assigned a weight of "2." The other categories, i.e., roof shape (Category 9), moisture/water inflow (Category 10) and all of the geologic related factors (Categories 1, 2 and 3), were each weighted at "1."

The RFRI for the mathematical expression shown in Eq. (1) produces a distribution where RFRI values approaching 0 would represent a very stable condition and those near 1 represent a very unstable condition. The minimum and maximum RFRI values without adjustment factors range between 17 and 83 (Fig. 2). If the maximum adjustment factors are applied to Categories 4, 6 and 7, an RFRI value of 146 is possible. It is also possible to calculate the RFRI if nothing is known about any of the defect categories. This produces a RFRI equal to 50, or equally between the stable and unstable conditions. This is a desired outcome of the mathematical expression. A logical outcome of these three conditions is to divide the RFRI into three risk categories: low, moderate and high (Fig. 2). It is important to note that the objective of this paper is to develop a method of ranking hazardous conditions. Therefore, it is inappropriate at this time to equate the proposed risk categories with a prescribed action.

Hypothetical case studies

Two case studies of the use of the proposed methodology to assess roof-fall hazards are given below. These cases are meant to demonstrate the use of the method through realistic scenarios. Engineering judgment, based on extensive underground stone mine investigations and related studies found within the literature, was used to identify:

- the number and kind of defect categories,
- the parameters used to determine an assessment value for each category,
- the weightings of categories and
- the adjustments for monitoring activities.

Case 1: Shear rupture surfaces with rock debris on the floor. One ground condition that adversely affects approximately 20 percent of U.S. underground stone mines is the occurrence of roof falls in conjunction with excessive levels of high horizontal stresses (Iannacchione, 2003). Mines with this problem often have a shear rupture surface in the immediate roof, i.e., first 2 m (6.6 ft) of strata, propagating in a direction perpendicular to the principal stress direction (Emery, 1964; Parker, 1966). The shear rupture surface is typically comprised of multiple surfaces that fracture the roof, forming a cutter or gutter type structure in the roof. As the rock fails, it falls to the ground below the shear rupture surface and begins to form a debris pile. The size of the pile depends on the size and shape of the shear rupture surface.

Case No. 1a (Table 3) assumes that the decision-makers at the mine have no knowledge of the defect categories discussed above with the following exceptions: the entry has a large shear rupture surface, i.e., >1 m (>3.3 ft) in length, and a continuous pile of rock debris has accumulated on the floor beneath the shear rupture surface. This first example produces an assessment value of "5" for defect Categories 4 and 8 and an assessment value of "3" for all other categories with a RFRI of 58.8 (Table 3). This is within the moderate RFRI level (Fig. 2).

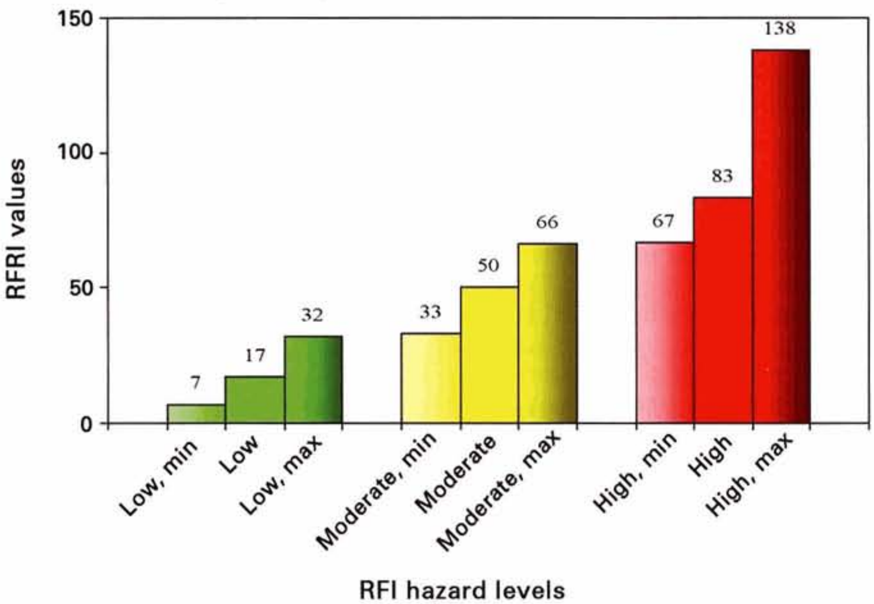
Table 2

Defect category weights.

Category number	Category description	Weight
1	Large angular discontinuities	1
2	Joint frequency	1
3	Roof layer thickness and bedding contact strength	1
4	Shear rupture surfaces	2
5	Joint separation	2
6	Lateral strata shifting	2
7	Vertical strata separation	2
8	Roof rock debris on floor	2
9	Roof shape	1
10	Moisture/ground water inflow	1

FIGURE 2

General RFRI ranges for high, moderate and low hazard levels.



Adding information about site conditions provides additional examples to help explain the proposed methodology and to test the method against the authors' experience. As more characteristics about this same site are obtained, such as favorable geologic conditions, smooth roof profile and dry roof conditions, and when drill holes show no lateral or vertical movement (Case No. 1b, Table 3), the RFRI falls to 31.6. This is just within the low RFRI level (Fig. 2).

Conversely, when additional information about the site conditions provides less favorable characteristics, such as drill holes showing lateral strata separation and elevated and clustered microseismic emissions (Case No. 1c, Table 3), the RFRI rises to 70.5. This is within the high RFRI level.

Case 2: Thinly bedded strata with weak bedding contacts. The impact of thinly bedded strata on roof rock stability is well documented (Hebblewhite and Lu, 2004). Add to this the wide room spans, >15 m (50 ft) and non-uniform use or rock reinforcement, and it is easy to see why this condition has been linked to many underground stone mine roof falls. Euler's formula provides general performance parameters for bedded stone roof beams where the critical stress defining the onset of beam buckling is highly dependent on beam thickness.

Case No. 2d (Table 3) assumes that the decision-maker has no knowledge of local defect categories with only one exception: the site is known to have thinly bedded strata with weak bedding contacts. This condition gives an assessment value of "5" for defect Category 3 and assessment values of "3" for all other categories with a

Table 3

RFRI values for two cases.

	Case 1						Case 2							
	a		b		c		d		e		f		g	
Catagory	**AV[1]**	**WAV[2]**	**AV**	**WAV**	**AV**	**WAV**	**AV**	**WAV**	**AV**	**WAV**	**AV**	**WAV**	**AV**	**WAV**
1	3	3	1	1	1	1	3	3	1	1	1	1	1	1
2	3	3	1	1	1	1	3	3	3	3	3	3	3	3
3	3	3	3	3	3	3	5	5	5	5	5	5	5	5
4	5	10	5	10	5	10	3	6	1	2	1	2	1	2
5	3	6	1	2	1	2	3	6	1	2	1	2	1	2
6	3	6	1	2	5	10	3	6	1	2	5	10	5	10
7	3	6	1	2	1	2	3	6	1	2	5	10	5	10
8	5	10	5	10	5	10	3	6	1	2	1	2	1	2
9	3	3	1	1	1	1	3	3	1	1	1	1	1	1
10	3	3	1	1	1	1	3	3	3	3	3	3	3	3
Subtotal		53		33		41		47		23		39		39
Multiply by 1.11		58.8		36.6		45.5		52.2		25.5		43.3		43.3
Adjustment		0		-5		25		0		0		15		30
RFRI		58.8		31.6		70.5		52.2		25.5		58.3		73.3

[1]AV = Assessment Values
[2]WAV = Weighted Assessment Values

RFRI of 52.2 (Table 3). This is within the moderate RFRI level (Fig. 2).

If closer inspection of the sites reveals more favorable characteristics (Case No. 2e, Table 3), the RFRI drops to 25.5. This is within the low RFRI level (Fig. 2). However, if sensor readings from this same area measure a constant downward roof defection (Case No. 2f, Table 3) or if measurements begin to measure an accelerating rate of roof deflection (Case No. 2g, Table 3), the RFRI can rise to 58.3 and 73.3, respectively. The latter is within the high RFRI level (Fig. 2).

Summary and conclusions

This study proposes a roof-fall-hazard-assessment method for underground stone mines that can be used to help manage miner exposure to unstable roof-rock conditions so that roof-fall-related injuries can be reduced. The underground stone-mining industry has an acute need for this capability because current roof-stability-assessment techniques are limited by difficulties with assessing conditions in high roofs, i.e., >7 m (>23 ft).

The proposed roof-fall-hazard-assessment technique is comprised of 10 defect categories that cover a range of geologic, mining induced, roof profile and moisture factors. Each category has a set of parameters that allow for the estimation of an assessment value between "1" and "5." These parameters are based on experience gained from visiting more than 50 different operating mines and from an investigation of relevant topics in the literature.

Important geologic factors affecting roof stability include large angular discontinuities, joint frequencies and roof-layer thickness and bedding-plane contact strength. In addition to these naturally occurring strata defects, a range of mining-induced failures, including shear rupture surfaces, joint separations, lateral strata shifting and vertical strata separation, directly impacts roof stability. A fundamental assessment of roof stability is also made by examining the profile of the roof, where its shape and the amount of fallen material provide evidence of what damage has occurred and, potentially, what damage will occur. Lastly, the influence of moisture on roof stability is determined by observing wetness and groundwater inflow conditions. These factors are determined with information readily available at any mine site with a means of accessing and drilling the roof.

In practice, much more information about the character and performance of a mine's roof can be made with monitoring data. These data are generally obtained from roof-deflection monitoring devices and some geophysical techniques, all of which help to detect and assess hazardous roof rock defects. In this roof-fall-hazard-assessment methodology, monitoring data are used to adjust assessment values. If monitoring information supports a more stable assessment of roof fall potential, then the RFRI is decreased. Conversely, information that indicates a less-stable condition yields a higher RFRI. In this way, decision-makers who know more about the site ground conditions are better able to make a more accurate hazard assessment.

The technique involves calculating a RFRI. Very stable conditions produce RFRI values approaching 0, while unstable conditions produce RFRI values approaching 100. In some cases, where significant adjustments are made, the RFRI may be in excess of 100. Three logical hazard levels are defined as low, moderate and high based on the RFRI values. Determining the particular risk for a specific underground stone entry will allow decision-makers to respond in a proactive and measured fashion to hazardous roof rock conditions, thereby lowering the potential for fall-of-ground injuries. ■

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